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Integrating travel demand modeling and flood hazard risk analysis for evacuation and sheltering

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ABSTRACT

In this paper, the risks of flooding hazards to the transportation system in urban Honolulu are assessed using a regional travel demand model (TDM). The approach serves to support understanding of evacuation and sheltering needs. Coastal and inland flooding hazard scenarios were modeled with four different hazard conditions. The inundation defined by the Maximum Envelope of High Water (MEOW) based on a hurricane that struck Hawaii and a tsunami run-up generated by historical earthquake events combined with a one-meter rise in sea level provided the worst possible coastal flooding scenario. A 500-year return period riverine flooding scenario was also included. The critical flooding hazard was transformed into a uniform 100 by 100 meter GIS based grid system. The Oahu Metropolitan Planning Organization (OMPO) TransCAD model for 2035 provided the origin and destination trips for eleven trip types including motorized and non-motorized travel modes. The OMPO model includes personal travel, travel to the airport, commercial vehicle travel and visitor travel sub-models. Origin and destination trip matrices for Traffic Analysis Zones (TAZ) and highway and transit assignment details were extracted from the model. The O-D trips and road segment traffic details were transformed to the spatial grid system and overlaid on the flooding hazard layer. The spatial categorization of the flooding along with the trip and travel data from the TDM provided a robust method to quantify and visualize risks to travelers and the transportation system. The analysis shows that flooding hazard scenarios have serious risks in Honolulu. First, a large portion of the study area is susceptible to flooding, threatening the population, economy, and infrastructure. Second, in addition to areas susceptible to flooding, a larger percentage of origins, destinations, trips and vehicle miles of travel (VMT) are affected because of the need to travel through the at-risk areas. Third, commercial, transit and non-motorized trips are disproportionately affected compared to auto travel. This paper demonstrates how hazard data and risk models can be integrated with travel demand models for purposes of evacuation planning and sheltering as well as emergency planning and hazard mitigation and adaptation of the transportation system to climate change.

1. Introduction

Flooding can have serious impacts on transportation systems. People may need to evacuate or take shelter in safer locations. Depending on the severity, flooding can cause lane closures and reduced system capacity leading to bottlenecks and congestion. In spite of the “turn around and don’t drown” messages, motorists are often swept away by floodwaters. Severe flooding may damage transportation infrastructure and reduce network connectivity as well as increased repair, maintenance, and capital construction costs. Road and transit agencies have often internalized the process of responding to road obstructions, closures, and other emergencies. Integration of hazard sciences in transportation planning is still in a nascent stage. Lately, however, efforts by the National Cooperative Highway Research Program (NCHRP) and the Transit Cooperative Research Program (TCRP) “A Guide to Planning Resources on Transportation and Hazards” [1] have encouraged the transportation and hazard management fields to better integrate hazards and risks into transportation system operation and management decision processes. NCHRP Report 525: Surface Transportation Security and TCRP Report 86: Public Transportation Security [2] provide guidelines for transportation operations. Events such as Hurricane Sandy, as well as the publication of Disaster Resilience: A National Imperative [3] point to the need to understand connections between the environment, climate change, hazards, critical infrastructure, and transportation. Schmidt and Meyer [4] have developed a conceptual framework for transportation agencies in considering climate change in each step of the planning process. It includes understanding the exposure, vulnerability, risk, and thresholds

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related to the performance of transportation systems under adverse conditions. They argue that in addition to understanding risks which can be thought of as the product of the frequency or likelihood of an event occurring times the consequences, it is important to establish "threshold" levels where an event would require a "significant response." The response, moreover, can be thought of not just in terms of actions or reactions to events such as flooding (evacuation, sheltering, road closure, deployment of rescue teams, etc.), but also the longer term "adaptation" strategies which may require protecting, accommodating or retreating from the at-risk areas [4]. The connections between extreme weather events, adaptation strategies, and increased maintenance costs have also been identified [5].

From a planning perspective, transportation systems are an essential critical infrastructure. Hazards that disrupt the transportation system can have a significant risk to the social and economic well-being of a community. Transportation lifelines have been studied because disruptions may come from "natural disasters, such as earthquakes, in general, to any kind of emergency due to a generic human or natural hazard or disaster, including meteorological or hydro-geological events, fires, floods, transport of hazardous materials, and industrial accidents…"[6]. An excellent review of research and practices related to evacuation planning and transportation modeling is provided by Murray-Tuite and Wolshon in which they compare studies in terms of factors associated with evacuation decision-making across different natural and man-made hazards [7]. This paper provides a summary of the factors related to evacuation decision-making and describes how the four step process (trip generation, distribution, mode choice and network assignment) can be applied to emergency management activities (response, preparedness, and mitigation). The paper also includes discussion of the interdisciplinary work combining behavioral and engineering sciences for verification, validation, and calibration of models. Previous evacuation studies were categorized as to factors associated with the evacuate versus stay decision. Traffic assignment tools used to estimate evacuation time and traffic have inherent limitations for evacuation modeling as most of the tools and models were developed for routine, not for evacuation travel. In order to improve the tools and models, Murray-Tuite and Wolshon [7] recommend model refinements and validation, interdisciplinary efforts among social scientist and engineers, and the use of new technologies for both effective warning systems and faster simulations for higher levels of resolutions. Another study integrating hazards and travel demand simulated the impacts of dirty bombs released in the D.C. metropolitan area on traffic (volumes, travel times, congestion, etc.) and the myriad of concerns for emergency managers and transportation planners [8]. Khademi et al. [9] provide a comprehensive review of studies related to transportation network vulnerability. They characterize the vulnerability studies based on the time (pre or post analysis of hazard), multiple links or single link failure, consideration for the link degradation, different indicators used to capture consequences, case study location, and the software used. They argued for redundancy-based isolation measures to assess the impact after a disaster event as the conventional network analysis methods may not be appropriate for post-disaster travel demand including evacuation behavior.

This study builds on previous research conducted by the authors which examined: flood risk from the combined effects of sea level rise and episodic hydro-meteorological and geophysical events, the risk and vulnerabilities to critical infrastructure including the transportation system, and evacuation travel times and distances for evacuation from these flooding events [10]. This paper strengthens the connections between transportation planning and emergency management, and builds on the use of travel demand models to better understand the risks to transportation systems from flooding hazards. While travel demand tools have typically been used for infrastructure and capital planning projects, or to evaluate strategies for managing transportation assets, this paper is concerned with hazards and management of critical infrastructure. The paper is focused on Hawaii, which conjures images of white sandy beaches and swaying palms, but is, unfortunately, one of the most exposed places to natural hazards (hurricanes, earthquakes, tsunamis, flooding, volcanoes, wildfire, etc.) as well as technological and man-made threats.

2. Data and methods

Davidson, et al. summarize the evolution and state of knowledge and practice with travel demand modeling, noting the differences between academic researchers and practical application modelers, with the former being focused more on "individual behaviors with a macroscopic resolution," while the latter being more concerned with "aggregate forecasts for transportation facilities as part of the planning process" [8]. They provide review and critique of the traditional four step process and identify the constituencies and applications and uses of travel demand modeling and policies for parking, tolling, high occupancy vehicle lanes, demand management, environmental justice, and other applications. Notably, disaster management applications were not included. Khademi et al. [9] framed a five stage model of transportation system vulnerability analysis which includes hazard characterization, damage, and failure prediction, as well as the assessment of consequences.

Similar to other MPOs (Metropolitan Planning Organizations), the Oahu Metropolitan Planning Organization uses a traditional travel demand model for capital planning activities. With efforts to build a multi-billion dollar, elevated fixed rail transit system in Honolulu, significant investments in data collection and modeling have occurred, providing further impetus for this study. Co-benefits associated with other uses and applications of the data and models should be considered. This analysis included four steps. The first two steps generated inputs. The subsequent step organized and transformed the model outputs and then the final step was to classify risks. Fig. 1, "Modeling Framework," illustrates the process in this study. The figure shows how the hazard science data are integrated with the travel demand modeling procedures.

The first step was to extract the trip files and vehicular traffic in the road network system for the study area. Only the most urbanized and built-up portion of the metropolitan area was examined. The study area, highlighted in the red box in Fig. 2, "Oahu MPO Road Network and Study Area," comprises urban Honolulu from Pearl Harbor to Diamond Head, including the major urban corridors of Waikiki, Kakaako, and Downtown. This figure also shows the main road network. Oahu Metropolitan Planning Organization (OMPO) is responsible for coordinating transportation planning on Oahu, which serves as the metropolitan planning organization for the two urbanized areas on Oahu (Honolulu and Kailua-Kaneohe) and coordinates transportation planning for the entire island [11]. The travel demand model is a TransCAD model (OMPO5.0) and accounts for resident travel, visitor travel, airport travel, and commercial vehicle travel. Data on travel demand is useful to understanding which travelers need to evacuate and where they are likely to be traveling. The model allows us to distinguish between the trip making behaviors of residents, visitors, and other vulnerable populations.

Box 1 within Fig. 1 summarizes the modeling sequence in the OMPO model. The Vehicle Ownership sub-model estimates the distribution of vehicle-ownership levels by each type of household based on the demographic characteristics for each of the 764 Traffic Analysis Zones (TAZ). The Trip Generation sub-model predicts the trip-productions and trip attractions, stratified trip purposes, based on calibrated trip-rates applied to the numbers and characteristics of households and jobs in each TAZ on the island. The OMPO resident travel model stratifies trips into eleven different trip purposes, including Journey-to-Work – Home-Based Work; Journey-to-Work – Home-Based Non-Work; Journey-to-Work – Non-Home-Based, Non-Work-Based; Journey-to-Work – Work-Based Non-Work; Journey-at-Work – Work-Based; Journey-at-Work – Non-Work-Based; Non-Work-Related – Home-Based College; Non-

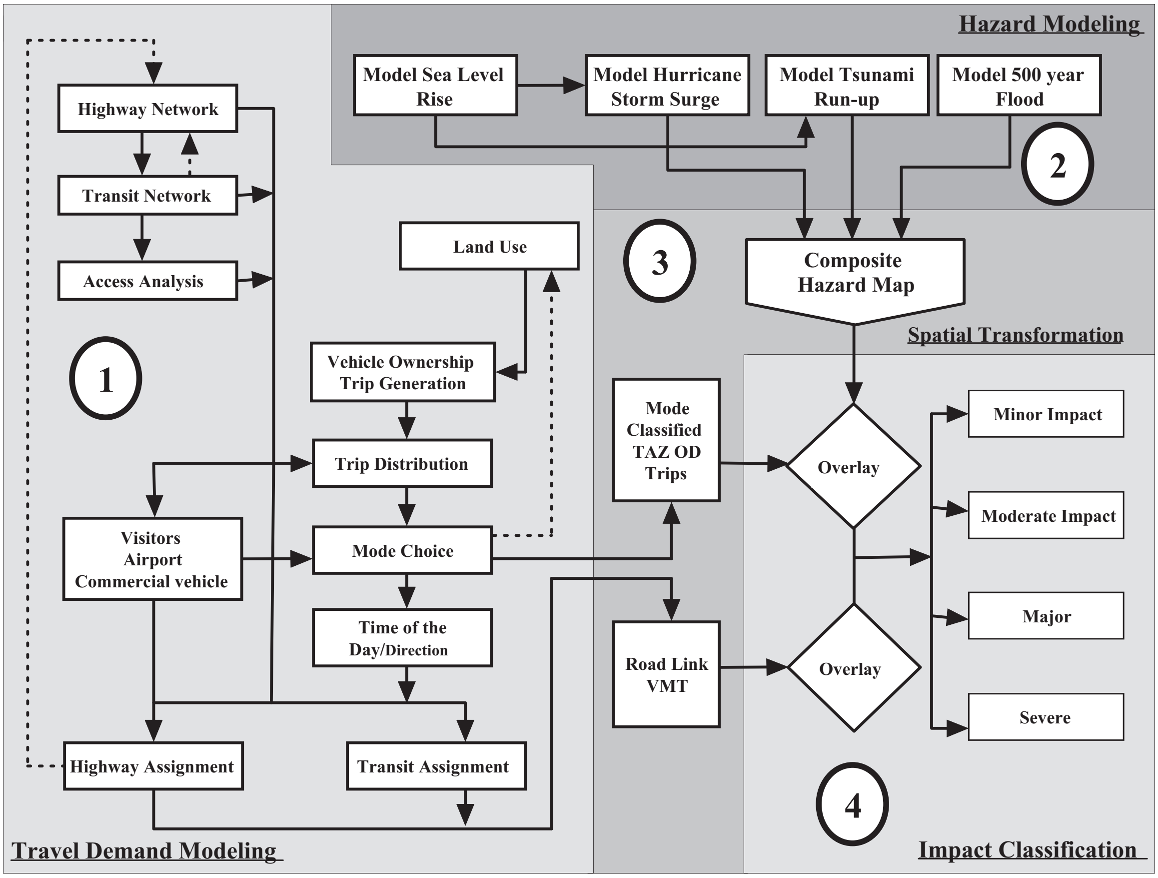

Fig. 1. Modeling framework.

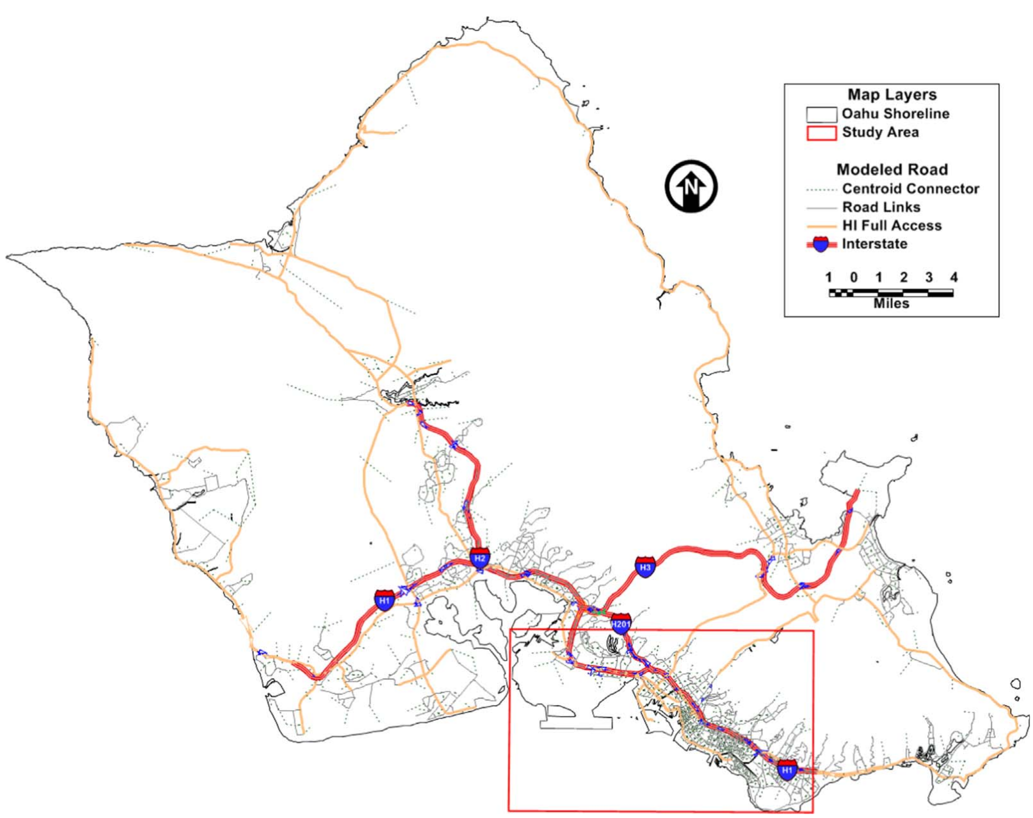

Fig. 2. Oahu MPO road network and study area.

Work-Related – Home-Based K-12 School; Non-Work-Related – Home-Based Shopping; Non-Work-Related – Non-Home-Based; Non-Work-Related – Home-Based Other. Each of the home-based trips gives valuable information the exposure of travelers in terms of the risks of flooding but also the types of trips and routes to be disrupted. The Trip Distribution sub-model applies a logit function to develop a zone-to-zone trip table for each trip purpose using the predicted trip productions and trip attractions in each zone together with zone-to-zone highway travel times. The Mode Choice sub-model uses a nested-logit function to estimate the shares of each zone-to-zone travel for 12 travel options. The alternative travel modes include auto, transit, and non-motorized travel. The selection includes options based on auto occupancies (1, 2, and 3+ person per vehicle), transit access-modes (walk, park/ride-formal, park/ride-informal, and kiss/ride), transit paths (local, premium, and guideway), walking, and bicycling and an option to select toll/non-toll choice. Commercial vehicle trips and airport trips and visitor trips are handled separately where trip generation, distribution, and mode choice are implemented simultaneously. The Time-of-Day/Direction sub-model distributes daily trip tables across the individual time-periods of the day and converts trip tables from production-attraction format to origin-destination (O-D)format. The Highway Assignment sub-model assigns the O-D vehicle trip table to the highway network and estimates the vehicular flow in the highway network for different time periods with several iterations until convergence based on the comparison of peak period travel time matrices and computation of averaged volumes [12].

The model was run for 2035, the longest time horizon currently available for the model. The model included planned and expected changes in the road network and results from the land use model. Altogether 11 person trip O-D files, 3 airport trip O-D files, 7 truck trip O-D files, and one visitor trip O-D files were produced. Each OD matrix may have up to 12 competing travel options. The files were collapsed into five categories: all auto travels; all transit travel; commercial vehicle travel; walk and bike. Since work travel and trips to shopping are major trip types, both auto and transit trips for these two categories were examined separately. Matrix aggregation tools in TransCAD [13] were used to aggregate and summarize more than 250 matrices with 764 TAZ origins and destinations trips. The final trip allocated geographic file by the Highway Assignment sub-model was also extracted for analysis.

The second stage as shown in Box 2 of Fig. 1 was to estimate coastal and riverine flooding. It included the effects of sea level rise. The hazard data, sea level rise estimates, storm surge and tsunami inundation areas were part of a National Oceanic and Atmospheric Adminstration (NOAA) Coastal Storms Program (CSP) project in partnership with the University of Hawaii Sea Grant College. Two modeled products: (i) hurricane storm surge with 1 m SLR; and, (ii) inundation due to the tsunami with one meter SLR were obtained from the NOAA CSP program [14].

The first model simulated a Category 4 hurricane, similar to Hurricane Iniki which struck Kauai in 1992, with a central pressure ranging from 910 to 970 mbar and maximum sustained winds of 90–150 mph as it tracked from open ocean to land. The model results show storm surge flow depth, flow speed, and inundation extent. Inundation was defined by the maximum of the Maximum Envelope of High Water (MEOW) which was used as one of the three inundation layers. The second model simulated maximum inundation levels based on five historical tsunamis that hit Hawaii: 1) The 1946 Aleutian earthquake (8.2 MW), 2) 1952 Kamchatka earthquake (9.0 MW), 3) 1957 Aleutian earthquake (8.6 MW), 4) 1960 Chile earthquake (9.5 MW), and 5) the 1964 Alaska earthquake (9.2 MW). A suite of numerical models [15–21] was used to generate the inundation depth results. Apart from the two CSP models, a third model for riverine flooding was included. The HAZUS-MH [22] riverine inundation model for the study region was calibrated for a 500 year return period.

The third step (Box 3, Fig. 1) included matching the three hazard layers with the TAZ geographic layer. This provided a unique challenge as each hazard layer had different types of data at varying spatial resolutions. The three hazard flood grid depth data were in raster format, and the TAZ geographic and road network traffic flow layers were in vector format. In previous research, the authors developed a vector based-polygon grid as a spatial unit of analysis [23–28]. The grid cell spatial framework has been tested and used for transit alignment analysis, economic and tourism planning, land use studies, and road safety analyses [23–28]. Using a uniform grid structure as the unit of analysis has advantages over other approaches which may have unevenly sized and irregular shaped units (i.e. traffic analysis zones and census tracts or block groups) by allowing for the application of statistical measures using a standard spatial unit of analysis. The three hazard layers and TAZ based O-D and road link traffic data were imported into a GIS [29] system. Several GIS routines were used to transfer the inundation layers to 100 m × 100 meter uniform vector grid file. Through geoprocessing, attributes for the grid polygon files were populated with hazard layer depth inundations for hurricane storm surge, tsunami run-up, and riverine flood. From the three hazards, a ruling hazard attribute for each grid cell was defined using the Eq. (1).

$$RHaZ_i = Max\begin{cases} max|SLR + Hurricane\ Storm\ Surge|_j \\ max|SLR + Tsunami\ Run - Up|_k \\ max|Riverine\ Flood|_l \end{cases} \tag{1}$$

Where *RHaz* is the ruling hazard for grid *i* which is the maximum of the three modeled hazards: hurricane storm surge with base SLR, tsunami run-up with base SLR and riverine flood resampled to grid *i* from their original spatial resolution of *j, k,* and *l* respectively. Geoprocessing routines were also used to transform TransCAD trip O-D in the TAZ geography and the road traffic geographic data into the grid polygons consistent with the spatial resolution of the ruling hazard data file.

The final step (Box 4, Fig. 1) consisted of the overlay of the ruling hazard and the trip and traffic data. Classification of the traffic vulnerability based on the flooding depth provided a means of assessing transportation risks. Grid cells were categorized into those: (i) not flooded; (ii) flooded less than 1 feet (minor); (ii) flooded between 1 to less than 2 feet (moderate); (iii) flooded between 2 to less than 5 feet (major); and, (iv) flooded beyond 5 feet (severe). Previous research has demonstrated that as little as one foot (30 cm) of water with a speed of 6 mph (10 km/h) or 10 feet per second (3 m/s) can move a typical car, and as little as 2 feet (60 cm) can float most cars [30]. Up to one foot of flooding was categorized as minor and subsequent higher depth categories are defined as moderate, major and severe. While minor flooding may only be inconvenient and not actually disrupt the traffic flow, it may contribute to traffic congestion and water related accidents. In the long-term, however, it could contribute to the weakening of the pavement subgrade and sub-base layers and lead to premature pavement failures. Moderate flooding will close the roadways to any vehicle traffic. In addition to traffic disruption, major and severe flooding will stress the drainage system and could lead to the structural failure of culverts and bridges and further loss of road sections.

The risks associated with the modeling results are described in the next section followed by a discussion and policy recommendations for mainstreaming hazard sciences into transportation planning to create a more robust and resilient transportation system. Finally, the conclusions are summarized and limitations and possible extensions of the study are included in the last section.

3. Results

3.1. Risks to trip origins and destinations

Fig. 3, “Total Trip Origins and Flooding Risk,” shows the trip origins aggregated for all travel modes, represented by a dot, with a hazard overlay according to the depth of flooding. Each dot represents 20 trips

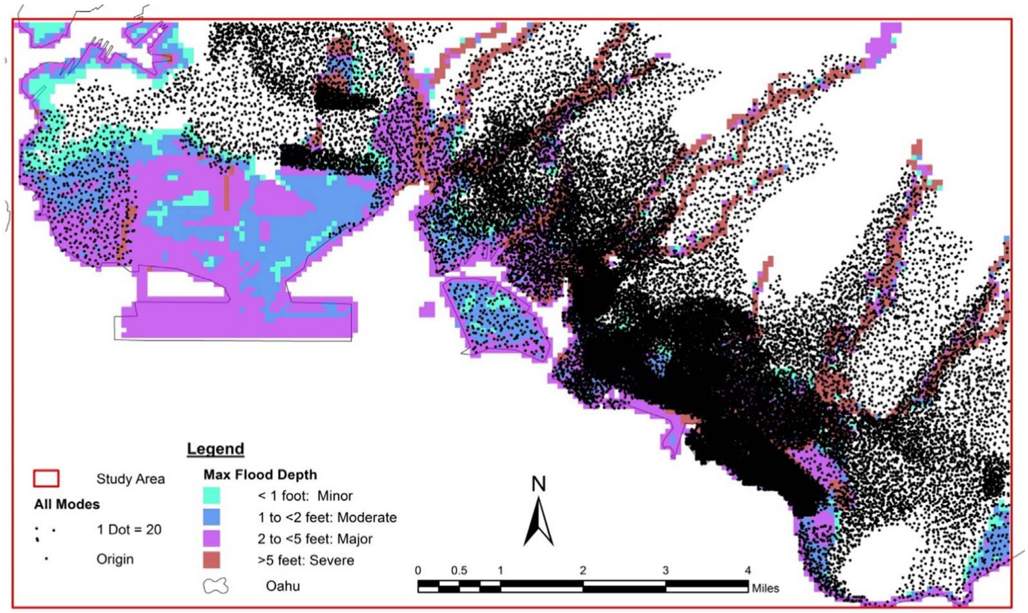

Fig. 3. Total trip origins and flooding risk.

and the shaded areas represent the four different levels of flooding. This provides an estimate of those who could shelter in place versus those who must evacuate.

Fig. 4, "Total Trip Destination and Flooding Risk," shows trip destinations aggregated for all modes of travel (again with each dot representing 20 trips). The figure also has the same four flooding risks. In comparing the two tables, it is evident that some areas have either origins or destinations but no risk in terms of flooding. The presence of parks and airports and open space is also reflected by the absence of trip dots. The pattern of origins and destinations also matches prevailing land use patterns especially in terms of the location of residences, businesses, and employment centers. Because the economy is oriented towards tourism which is largely within the coastal zone, it is evident that the trip origins and destinations are in close proximity to Waikiki and other established business districts.

Table 1, "Work Auto and Transit Trips and Flooding Risk," and Table 2, "Shopping Auto and Transit Trips and Flooding Risk," summarize the risks to trip origins and trip destinations for two important trip types: (i) work trips; and, (ii) shopping trips for both auto and transit. In reading these tables, it should be noted that the column headings relate to the risk of flooding (no, minor, moderate, major, severe) as well as the total exposed areas and the cumulative risk of the flooded areas. The row headings pertain to both the grid characteristics as well as the trip origins and destinations organized by work auto trips and then work transit trips. Depending on how much warning travelers have, they may need to evacuate and take shelter from their homes or work or shopping locations.

In Table 1, 42% of the grids in the study area are at risk of flooding. The number of trip origins equals the number of trip destinations (684,772), but 47.2% of the auto work origins are in the at risk zone, while 69.2% of the auto work destinations are at risk of flooding. So the point here is that many more workers are exposed to flooding than households. Unlike the origin and destination trips for the whole island, the study area origin and destination trips do not match, as the study area only includes a portion of the total island wide model. The total origin work trips generated in the study area is only 31% (214,551) of

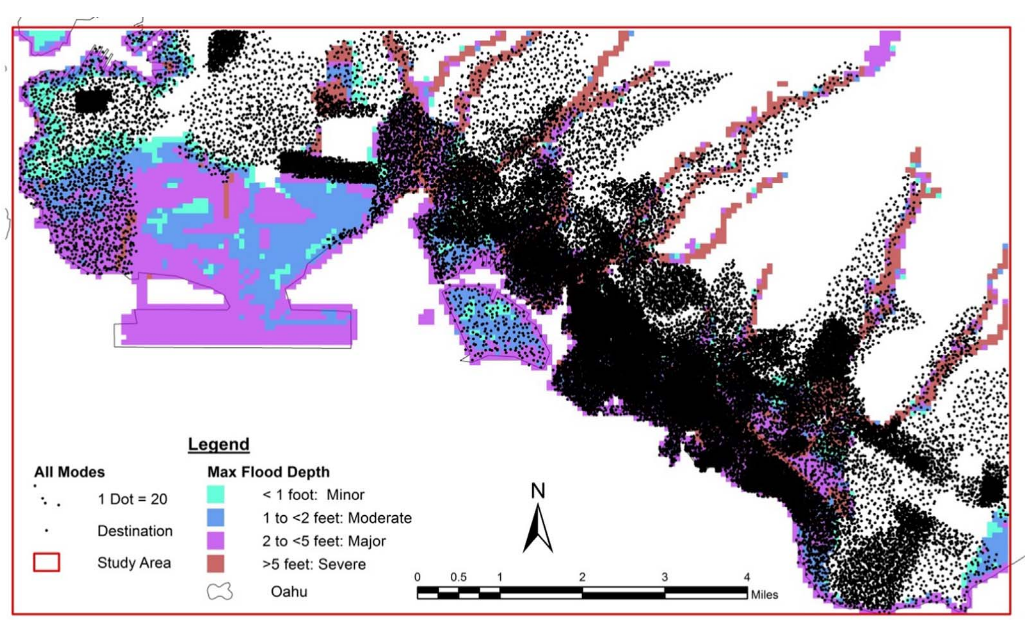

Fig. 4. Total trip destinations and flooding risk.

Table 1
Work auto and transit trips and flooding risk.

Description (1)	Unit (2)	No flood (3)	Minor < 1 foot (4)	Moderate 1 to < 2 feet (5)	Major 2 to < 5 (6)	Severe > 5 feet (7)	Total (8)	Risk (9)
Grids in – Study Area	No	8102	625	1361	2726	1155	13,969	
Proportion of Grid in – Study Area	%	58.0%	4.5%	9.7%	19.5%	8.3%	100%	42.0%
Average depth	Feet	0	0.5	1.5	3.1	10.5	3.94	
Work Auto Origin-Study Area	Trips	113,213	9455	21,299	36,928	33,656	214,551	
Work Auto Origin-Oahu	Trips	NA	NA	NA	NA	NA	684,772	
Proportion of - Study Area	%	53%	4%	10%	17%	16%	100%	47.2%
Proportion of Oahu	%	NA	NA	NA	NA	NA	31%	
Work Auto Destination-Study Area	Trips	119,414	33,986	59,758	128,829	45,618	387,605	
Work Auto Destination-Oahu	Trips	NA	NA	NA	NA	NA	684,772	
Proportion of - Study Area	%	31%	9%	15%	33%	12%	100%	69.2%
Proportion of Oahu	%	NA	NA	NA	NA	NA	57%	
Work Transit Origin- Study Area	Trips	15,392	1927	5241	9536	6831	38,927	
Work Transit Origin-Oahu	Trips	NA	NA	NA	NA	NA	64,896	
Proportion of - Study Area	%	40%	5%	13%	24%	18%	100%	60.5%
Proportion of Oahu	%	NA	NA	NA	NA	NA	60%	
Work Transit Destination- Study Area	Trips	14,004	4649	8316	14,241	5319	46,530	
Work Transit Destination-Oahu	Trips	NA	NA	NA	NA	NA	64,896	
Proportion of - Study Area	%	30%	10%	18%	31%	11%	100%	69.9%
Proportion of Oahu	%	NA	NA	NA	NA	NA	72%	

the total work trip in the island (684,772) whereas the study area attracts 57% (387,605) of all work trips (684,772). This shows the importance and criticality of the study area and by extension the transportation system within the area to the economy of the island. In terms of transit work trips, the proportions in the flood zones for both origins (60.5%) and destinations (69.9%) are higher than the auto work trips. With Table 2, which looks at shopping trips for both auto and transit, a similar pattern emerges with the proportion of auto shopping trip origins and destinations (40.7%, 38.4%) in the flood zone lower than that for transit trips (58.5%, 84.1%). This is an important finding because it reveals that transit users tend as a group to be more exposed and vulnerable to flooding hazards than those traveling by automobile.

Table 3, "Combined Auto, Transit and Commercial Vehicle Trips and Flooding Risk," summarizes the combined risks of flooding scenarios on all automobile, transit, and truck traffic. In terms of total automobile trips, 62% of all origins and 66.5% of all destinations are potentially affected by flooding. With total transit trips, the respective values are 78.5% and 69.9%. For truck traffic, the proportions of origins and destinations affected by flooding scenarios are 71.7% and 69.9%. These are significant threats both in terms of the study area but also as a proportion of the total trip making of the entire island.

Table 4, "Non-Motorized Trips and Flooding Risk" summarizes the risks to trip origins and destinations for pedestrian and bicycle travel. Notably, 77% of pedestrian origins and 78.6% of pedestrian destinations are within the at risk zone. For bicyclists, the proportions are 57% and 62%.

In a previous study, the authors examined the population and shelter needs at different levels of flooding (i.e., minor, moderate, major, and severe), as well as evacuation factors (i.e., miles traveled to evacuate, evacuation time cost, evacuation distance accessibility, and time burden) associated with these flood levels [10]. It was determined that, based on the 2010 census population, at minor flooding level (< 1 ft.), 14,974 people will be at risk, while at the severe flood levels (> 5 ft.) there will be 150,301 people at risk. With minor flooding, there will be a total number of 41 shelters that need to be used, and two of them will be flooded, and with major flooding, 17 out of the 41 shelters needed will be flooded. In terms of miles traveled to evacuate, at the minor flooding level, a total of 6723 miles of travel were required

Table 2
Shopping auto and transit trips and flooding risk.

Description (1)	Unit (2)	No flood (3)	Minor < 1 foot (4)	Moderate 1 to < 2 feet (5)	Major 2 to < 5 (6)	Severe > 5 feet (7)	Total (8)	Risk (9)
Grids in - SA	No	8102	625	1361	2726	1155	13,969	
Proportion of Grid in - SA	%	58.0%	4.5%	9.7%	19.5%	8.3%	100%	42.0%
Average depth	Feet	0	0.5	1.5	3.1	10.5	3.94	
Shop Auto Origin-SA	Trips	27,083	1923	3601	6097	6986	45,689	
Shop Auto Origin-Oahu	Trips	NA	NA	NA	NA	NA	178,580	
Proportion of - SA	%	59%	4%	8%	13%	15%	100%	40.7%
Proportion of Oahu	%	NA	NA	NA	NA	NA	26%	
Shop Auto Destination-SA	Trips	36,795	3603	5602	6328	7421	59,749	
Shop Auto Destination-Oahu	Trips	NA	NA	NA	NA	NA	178,580	
Proportion of - SA	%	62%	6%	9%	11%	12%	100%	38.4%
Proportion of Oahu	%	NA	NA	NA	NA	NA	33%	
Shop Transit Origin-SA	Trips	2263	253	674	1339	964	5494	
Shop Transit Origin-Oahu	Trips	NA	NA	NA	NA	NA	12,412	
Proportion of - SA	%	41%	5%	12%	24%	18%	100%	58.8%
Proportion of Oahu	%	NA	NA	NA	NA	NA	44%	
Shop Transit Destination-SA	Trips	1327	367	816	4986	866	8362	
Shop Transit Destination-Oahu	Trips	NA	NA	NA	NA	NA	12,412	
Proportion of - SA	%	16%	4%	10%	60%	10%	100%	84.1%
Proportion of Oahu	%	NA	NA	NA	NA	NA	67%	

Table 3
Cumulative auto, transit and commercial vehicle trips and flooding risk.

Description (1)	Unit (2)	No flood (3)	Minor < 1 foot (4)	Moderate 1 to < 2 feet (5)	Major 2 to < 5 (6)	Severe > 5 feet (7)	Total (8)	Risk (9)
Grids in - SA	No	8102	625	1361	2726	1155	13,969	
Proportion of Grid in - SA	%	58.0%	4.5%	9.7%	19.5%	8.3%	100%	42.0%
Average depth	Feet	0	0.5	1.5	3.1	10.5	3.94	
All Auto Origin-SA	Trips	175,218	18,561	50,946	156,306	60,535	461,566	
All Auto Origin-Oahu	Trips	NA	NA	NA	NA	NA	1,260,404	
Proportion of - SA	%	38%	4%	11%	34%	13%	100%	62.0%
Proportion of Oahu	%	NA	NA	NA	NA	NA	37%	
All Auto Destination-SA	Trips	239,284	51,657	94,131	249,866	78,464	713,401	
All Auto Destination-Oahu	Trips	NA	NA	NA	NA	NA	1,260,404	
Proportion of - SA	%	34%	7%	13%	35%	11%	100%	66.5%
Proportion of Oahu	%	NA	NA	NA	NA	NA	57%	
All Transit Origin-SA	Trips	26,425	3257	16,224	63,158	13,725	122,789	
All Transit Origin-Oahu	Trips	NA	NA	NA	NA	NA	255,845	
Proportion of - SA	%	22%	3%	13%	51%	11%	100%	78.5%
Proportion of Oahu	%	NA	NA	NA	NA	NA	48%	
All Transit Destination-SA	Trips	53,830	9298	20,002	79,054	16,830	179,015	
All Transit Destination-Oahu	Trips	NA	NA	NA	NA	NA	255,845	
Proportion of - SA	%	30%	5%	11%	44%	9%	100%	69.9%
Proportion of Oahu	%	NA	NA	NA	NA	NA	70%	
Truck Origin-SA	Trips	37,632	12,066	23,193	45,191	14,884	132,966	
Truck Origin-Oahu	Trips	NA	NA	NA	NA	NA	220,217	
Proportion of - SA	%	28%	9%	17%	34%	11%	100%	71.7%
Proportion of Oahu	%	NA	NA	NA	NA	NA	60%	
Truck Destination-SA	Trips	39,328	11,901	21,470	42,574	15,251	130,523	
Truck Destination-Oahu	Trips	NA	NA	NA	NA	NA	220,217	
Proportion of - SA	%	30%	9%	16%	33%	12%	100%	69.9%
Proportion of Oahu	%	NA	NA	NA	NA	NA	59%	

Table 4
Non-motorized trips and flooding risk.

Description (1)	Unit (2)	No flood (3)	Minor < 1 foot (4)	Moderate 1 to < 2 feet (5)	Major 2 to < 5 (6)	Severe > 5 feet (7)	Total (8)	Risk (9)
Grids in - SA	No	8102	625	1361	2726	1155	13,969	
Proportion of Grid in - SA	%	58.0%	4.5%	9.7%	19.5%	8.3%	100%	42.0%
Average depth	Feet	0	0.5	1.5	3.1	10.5	3.94	
Walk Origin-SA	Trips	114,525	18,484	62,131	238,637	63,203	496,980	
Walk Origin-Oahu	Trips	NA	NA	NA	NA	NA	762,178	
Proportion of - SA	%	23%	4%	13%	48%	13%	100%	77.0%
Proportion of Oahu	%	NA	NA	NA	NA	NA	65%	
Walk Destination-SA	Trips	112,698	26,304	54,540	286,406	46,969	526,917	
Walk Destination-Oahu	Trips	NA	NA	NA	NA	NA	762,178	
Proportion of - SA	%	21%	5%	10%	54%	9%	100%	78.6%
Proportion of Oahu	%	NA	NA	NA	NA	NA	69%	
Bike Origin-SA	Trips	9581	1136	2775	5221	3563	22,276	
Bike Origin-Oahu	Trips	NA	NA	NA	NA	NA	43,921	
Proportion of - SA	%	43%	5%	12%	23%	16%	100%	57.0%
Proportion of Oahu	%	NA	NA	NA	NA	NA	51%	
Bike Destination-SA	Trips	9043	1641	2978	7047	3134	23,844	
Bike Destination-Oahu	Trips	NA	NA	NA	NA	NA	43,970	
Proportion of - SA	%	38%	7%	12%	30%	13%	100%	62.1%
Proportion of Oahu	%	NA	NA	NA	NA	NA	54%	

to evacuate, as opposed to 196,420 miles at severe flood levels. During minor flood waters, the evacuation time costs of the evacuating population is a total of 1390 h (83,420 min), as opposed to during severe flood levels where the time cost is 3274 h (196,420 min) [10].

3.2. Risks to the road system and VMT

Fig. 5, "Modeled Average Daily Traffic," shows the traffic conditions in the study area based on the model runs. The maximum predicted flow is 158,928 vehicles per day for the section of the H1 freeway in the urban core. Although this study area is small in comparison to the total area of the island, these road links carry high volumes of traffic.

Fig. 6, "Road Length and VMT Flooding Risk," shows the roadway exposure to the flooding hazard. Table 5, "Road Length, VMT and Flooding Risk," summarizes the flooding risk in terms of the length and VMT. Table 5 shows that 45.2% of the study area roadway length is potentially affected by flooding. As the table reveals, 23 miles out of the total 368 miles of roadway in the study area is potentially affected by minor flooding, 33 miles by moderate, 68 miles by major, and 43 miles by severe flooding. Based on the model results, of the 5.9 million miles of daily VMT (vehicle miles traveled), 46.8% occurs within areas of potential flooding. One important point to note is that OMPO road network is conflated to the Oahu street network and thus accurately represents the geographical location of the road link. However, the OMPO road network is not an exhaustive inventory of all the roads. As with any regional travel model, the road network represented in the

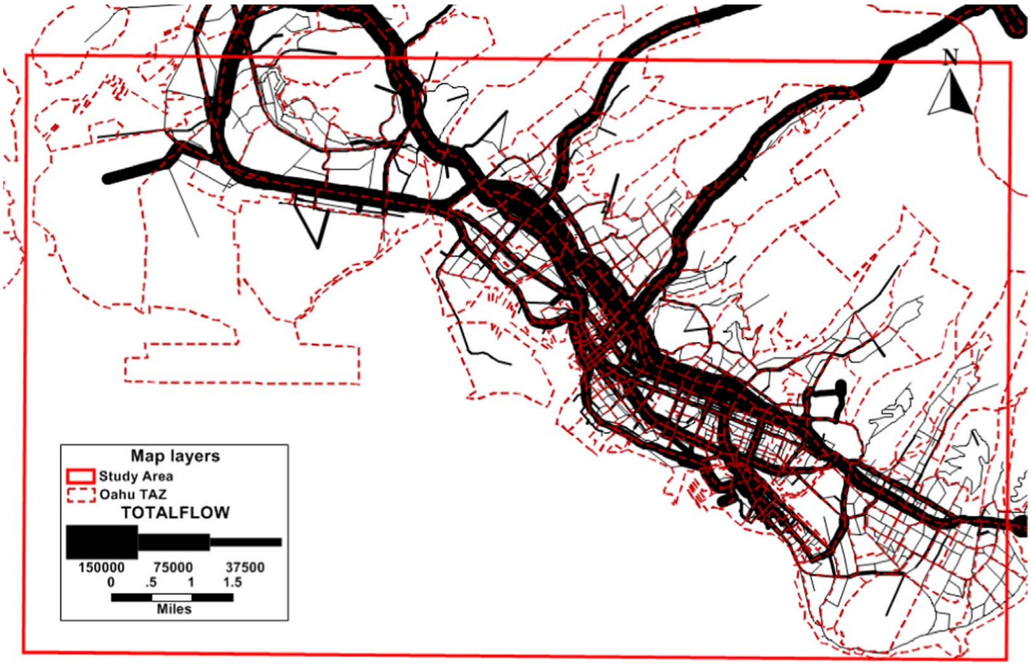

Fig. 5. Modeled average daily traffic.

OMPO model is only a sub-set of the total road network and a large number of local low-trafficked roads are not represented in the model. Thus the actual flood affected road length calculated in Table 5 is a conservative estimate.

4. Discussion

There are three different uses for the analyses presented in this paper. The first is for emergency management and disaster preparedness. The second focuses on mitigation and adaptation to longer term threats associated with flooding and other hazards. The third entails future refinements, research, and extensions of the work presented here.

For emergency management, it is important to think about the risks and the issues associated with response, operations and preparedness. Flooded roadways mean that businesses and households will also be flooded. It is important to not just identify homes and activity locations, but to also account for the many people on the road moving through the transportation network. In some areas, evacuation of travelers will need to occur. In other areas, rescue operations may be necessary. The deployment and routing of emergency vehicles, equipment and resources need to take into consideration the risks to key lifelines and travel routes to avoid flooded areas. The problems associated with flooded and stalled vehicles or vehicles swept away by flooding which could hamper rescue efforts also need to be considered. The cascading effects of power outages, loss of traffic signal controls, and disruption of communication channels will also require changes in the management of transportation systems. Flooded roadways will impede the work of first responders (police, fire, EMS, etc.) and increase response times as well as demands for real time situational awareness. Having an understanding of which roads are most likely to flood will only serve to improve performance during emergencies. Based on this analysis, we

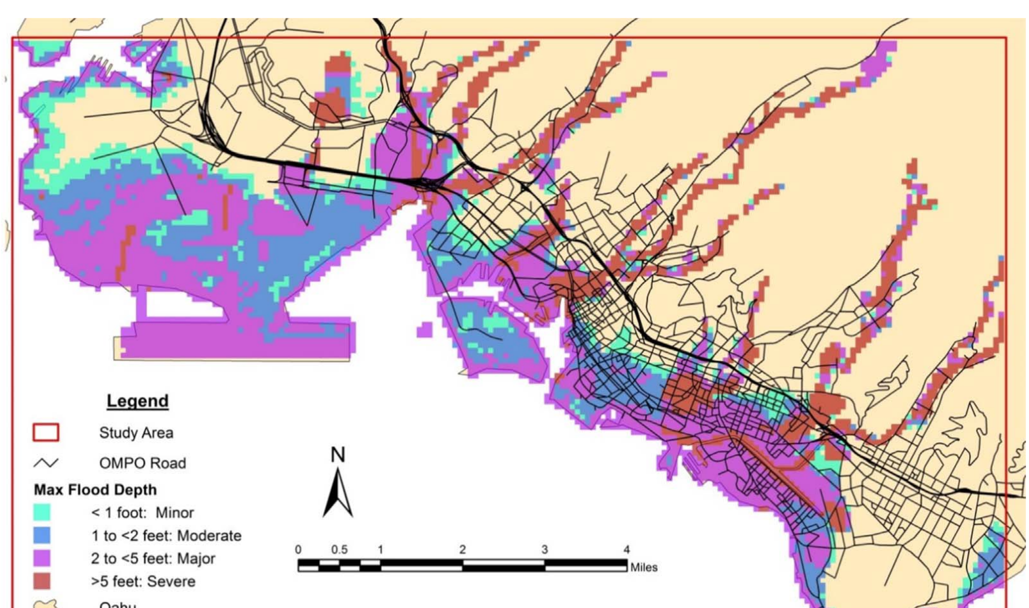

Fig. 6. Road length and VMT flooding risk.

Table 5
Road length, VMT and flooding risk.

Description (1)	Unit (2)	No Flood (3)	Minor < 1 foot (4)	Moderate 1 to < 2 feet (5)	Major 2 to < 5 (6)	Severe > 5 feet (7)	Total (8)	Risk (9)
Grids in SA	No	8102	625	1361	2726	1155	13,969	
Proportion of Grid in SA	%	58.0%	4.5%	9.7%	19.5%	8.3%	100%	42.0%
Average depth	Feet	0	0.5	1.5	3.1	10.5	3.94	
Road Link Length in SA	Mile	202	23	33	68	43	368	
Proportion of Road Link Length in SA	%	54.8%	6.1%	9.0%	18.4%	11.6%	100%	45.2%
OMPO Road Length for Oahu	Mile	NA	NA	NA	NA	NA	1201	
SA Road Length as a Proportion of Road Length in Oahu	%	NA	NA	NA	NA	NA	30.6%	
Daily travel in SA	VMT	3,145,872	424,062	421,190	1,098,085	824,644	5,913,853	
Proportion of Travel in SA	%	53.2%	7.2%	7.1%	18.6%	13.9%	100%	46.8%
OMPO Daily Travel in Oahu	VMT	NA	NA	NA	NA	NA	17,602,777	
SA Travel as a Proportion of Travel in Oahu	%	NA	NA	NA	NA	NA	33.6%	

can also estimate the number of people that should also shelter in place.

Planning models and simulation techniques depend on variables that may not fully represent real world conditions and may not be useful for operational decision-making. Using information and results from a calibrated and validated transportation demand model such as the Oahu MPO travel demand model along with real time situational awareness is, however, an improvement over arbitrary decision-making. These results quantifying flooding risk in a hazard differentiated spatial grid framework can be used to develop higher resolution and hazard specific evacuation and sheltering plans. While this paper focused on the combined effects and a "ruling hazard" approach to analyze the effects of sea level rise, storm surge, riverine flooding, and tsunami, it is also possible to separate out the various hazards and threats and evaluate them individually, which may need different guidance and procedures for each hazard. A short-notice event such as locally generated tsunami may require a different set of operational procedures than a slower onset event with more warning time such as a hurricane or storm system or sea level rise. Flooding threats affect a disproportionate share of the trip making activity whether measured in terms of origins and destinations for automobile, transit, pedestrian, bicycle and truck travel, or by the proportion of grid areas or the length of the roadway or the VMT impacted by flooding.

Another key finding is the differential levels of exposure for transit users. Flooding risks for different trip types and modes for all flood hazard events were estimated. Transit users, as well as pedestrians, are more exposed than automobile users. That truck traffic is also more exposed is not surprising given Honolulu's patterns of urbanization, economic development, and business location. Given the nature of disasters and the disproportionate risk to elderly, minority, low income, and persons with disabilities, more attention needs to be paid to issues of mobility and accessibility to transport services, especially in the event of flooding. Once again, this analysis signals the need to focus attention on vulnerable populations, but through the lens of the transportation planner. It is important to understand trip making behavior because flooding can occur suddenly and may affect different travelers depending on where they are at different times of the day.

The second dimension involves understanding how this analysis can be used to better mitigate hazards and adapt to longer-term environmental changes. Embedded in this analysis is the assessment of transportation system vulnerabilities and risks. Looking at the tables there are frequencies and probabilities and consequences for travelers affected by flooding. In addition to measuring the risks to households or businesses, it is important to recognize that people moving about an urban area also have evacuation and sheltering requirements. The major contribution of this paper is to quantify the risks to the transportation system of different flooding scenarios. While the low and moderate risk scenarios are much more common, the major and severe flooding are rarer, but the consequences are more significant in terms of the total area as well as in terms of the measured risks to the transportation system. Another way of using these data is to identify the "thresholds" for mitigation and adaptation. Herein lies the challenge: should we focus on high probability, low consequence events or low probability, high consequence events. Roadway improvements or preventative maintenance or mitigation actions for frequently flooding areas may make sense initially but without a longer-term plan for "protecting, accommodating or even retreating" from at risk areas, the potential for more catastrophic losses could be great. While the data and models for travel demand estimation have been used for analyzing the benefits and costs of new transportation infrastructure, clearly, these tools can be applied for assessing decisions such as improved drainage systems, building flood resistant roadways, elevating transportation links, and even relocating vulnerable roadways. Among the most "adaptable" include bus and paratransit routes as well as redesigned pedestrian and bicycle routes.

A key message which arises from this analysis is the interdependencies of land use and transportation systems. Whether construed in terms of origins or destinations or trip purposes (work, shopping, school, etc.), it is evident that land use, development, and human activities drive trip-making and the movements of people and goods across time and space. This observation opens the door to the third dimension for this paper which involves extensions and future research needs. Future research could focus on performance functions that estimate consumer surplus in addition to time and flow [31] or include unexpected events with multiple uncertainties [32].

As travel demand models progress toward increased sophistication in terms of activity based structures or tour-based (as opposed to trip based) modeling as well as micro-simulations, it is evident that forecasting which looks at the differences at the micro-level is especially critical and relevant to emergency management and transportation system resilience. Knowing how individuals will respond to changes and conditions whether in terms of evacuation decision-making or routing decisions during flooding have important consequences not just in terms of system performance but also, potentially, in terms of whether or not travelers are killed, injured, or experience other losses. In attempting to determine hazard exposure, it is critical to know not just where people are at various times of the day, but also how they travel and the routes that they take. It's important to see all of this not just in terms of the threat and hazard exposure, but also in terms of what can be done to better model and understand the travel behavior before, during, and after events such as roadway flooding. While this paper focused on flooding as an illustrative case, it is also possible to look at other types of disasters including travel behavior associated with earthquakes or wildfires or terrorism which can disrupt transportation networks.

5. Conclusions

This paper demonstrates the use of travel demand data for

estimating evacuation and sheltering requirements. It was based on data and models from Honolulu. More attention could have gone toward model validation and calibration. There are alternatives to TransCAD which also could have been explored. Certainly, the behavior of individuals during a storm may not necessarily match that of those who were surveyed and included for purposes of this regional travel demand model. Some might argue that using the travel forecasts for 2035 makes less sense than either a shorter or longer time frame. The analysis based on the 2035 travel forecast may be appropriate for long-term planning purposes, specifically for the year 2035, whereas an analysis based on existing demography and travel patterns are more relevant for the development of current evacuation and sheltering plans. These are all adjustments and refinements which could be attended to in future analyses. The intent here is to open up a line of inquiry and potential collaboration between travel demand modelers and the emergency management community. This is consistent with efforts to embrace the “whole community” in disaster management, but also recognizes the importance of transportation assets, data, models, and systems in building resilience.

The research present is relevant to broader efforts to understand and build resilience systems. The United Nation Office for Disaster Risk Reduction (UNISDR) [33] defines the aim of Disaster Risk Reduction (DRR) is “to reduce the damage caused by natural hazards like earthquakes, floods, droughts, and cyclones, through an ethic of prevention.” DRR includes all activities that minimize vulnerabilities and disaster risks such as disaster management, disaster mitigation, and disaster preparedness. Recent international agreements and initiatives such as the Sendai Framework for Disaster Risk Reduction 2015–2030 [34] identifies targets to reduce disaster related mortality and economic losses. The Rockefeller 100 Resilient Cities [35,36] initiative adopts comprehensive and multidimensional approaches to make cities resilient beyond that of traditional hazard risk assessment or sustainable development initiatives. While the research presented in this paper focuses on Honolulu, there are many other cities exposed to flooding, sea level rise, and coastal hazards. Understanding not just the risks from flooding, but also the impacts on the transportation system is a vital component of minimizing vulnerabilities and preparing for, managing, and preventing disasters.

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